

Sustainable Civil Engineering Structures and Construction Materials, SCESCM 2016

Forensic assessment on near surface landslide using electrical resistivity imaging (ERI) at Kenyir Lake area in Terengganu, Malaysia

Mohd Hazreek Zainal Abidin^{a,*}, Aziman Madun^a, Saiful Azhar Ahmad Tajudin^b,
Mohd Fakhurrazi Ishak^c

^a*Faculty of Civil and Environmental Engineering, Universiti Tun Hussein Onn Malaysia, Johor 84600, Malaysia*

^b*Research Center for Soft Soil, Universiti Tun Hussein Onn Malaysia, Johor 84600, Malaysia*

^c*Faculty of Engineering Technology, Universiti Malaysia Pahang, Pahang 26600, Malaysia*

Abstract

Electrical resistivity method which was championed by geophysicist has increasingly popular in civil engineering application due to its efficiency in term of cost, time and data coverage. This study performed with particular reference to electrical resistivity imaging (ERI) in evaluating the slope failure at Kenyir Lake, Malaysia. During the data acquisition, two lines of ERI was performed using ABEM Terrameter LS set of equipment based on Schlumberger array. Moreover, electrical resistivity anomaly was managed to detect the presence of geological structure with particular reference to fault and rock discontinuities which associated to low resistivity anomaly. The heterogeneous of the subsurface material presented using integrated analysis of ERI and borehole data enabled forensic assessment of the landslide. The combination of heavy rainfall and existing geological structure (weakness zone) was believed to be a major factor which triggered this failed slope. This result was applicable to assist the geotechnical engineer in design concept recommendation of the slope remediation with fast, less cost and wide data coverage. Finally, ERI results with borehole verification was applicable to be adopted in landslide forensic assessment based on slope geomaterials stiffness variations generated after the slope movement.

© 2017 Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Peer-review under responsibility of the organizing committee of SCESCM 2016.

Keywords: Electrical resistivity method; electrical resistivity imaging; forensic assessment; landslide; resistivity anomaly; geological structure

* Corresponding author.

E-mail address: hazreek@uthm.edu.my

1. Introduction

Forensic assessment in engineering is the investigation of materials, products, structures or breakdown components which may cause injury or property damage. Engineering forensic investigation used to identify causes of failure for rehabilitation or mitigation purposes or to assist a court in determining the facts of an incident. The process of engineering forensic assessment involve with investigation and data collection related to the materials, products, structures or components that failed such as inspections, collecting evidence, testing and measurements, developing models, obtaining prototype model and conducting experiments. Specifically in geotechnical forensic engineering, it involves analysis of a project, site conditions, or construction from a geotechnical point of view which can be performed during the design phase (e.g. checking calculations and engineering assumptions) or during or after the construction of the project (e.g. providing quality assurance or address issues that arise during or after construction) for rehabilitation purposes. Common related issues involving geotechnical forensic evaluation were ground settlement, slope instability, foundation failure, excavation failure, collapsible soil, soil corrosion, etc. Forensic geotechnical engineering is growing increasing important in most of the countries where the foundation failures may lead to litigation and even criminal action [1].

Conventionally, site investigation data used in ground instability assessment was based on borehole exploration method [2-4]. However, several limitations have been experienced related to conventional method due to its high cost, time consuming and limited data coverage. Furthermore, conventional method was based on the drilling data which represent only single point information (1-D) at the actual drilling location thus enables some degree of uncertainties due to the boring interpolation which consider critical in a complex geological area [5-7]. Lots number of drilling point was required in order to obtain higher accuracy of the subsurface results thus increasing cost and time of the project. Moreover, conventional method was based on drilling process which able to increased site damageability due to its destructive approach in field exploration. Therefore, the solutions to these challenges will require multidisciplinary research across the social and physical sciences and engineering [8]. Hence, geophysical method offers the chance to overcome some of the problems inherent in more conventional ground investigation techniques [9]. Geophysical techniques contributes several advantages such as it can be performed fast and low cost and has the ability to cover greater areas more thoroughly [10-13] and [6].

As reported by [14], Cummings and Clark have found that geophysical instruments used in landslides evaluation were heavily based on seismic refraction and electrical resistivity methods thru basis of interpretation of obvious different physical properties of the sliding materials compared to the underlying undisturbed sediments or bedrock. However, seismic refraction method experienced several limitations due to its physics fundamental constraint such as hidden and thin layer, inadequate sources, noisy and involve lots of data reduction thus promoting to increase the results ambiguity. Nowadays, electrical resistivity imaging (ERI) has greatly being improved in term of survey coverage, field measurement, processing techniques thus applicable to resolve complex geological structure compared to the previous sounding technique [15]. From the past, electrical resistivity survey has widely used as a tool for investigating the condition of the slope especially in landslide studies during the pre and post construction stages [16-21]. According to [22], landslides areas has widely being investigated using ERT technique with the aim to reconstruct the slope and body geometry, to locate the possible sliding surface, to identify vulnerability surfaces, to estimate the slide material thickness and to detect areas with high water content. According to [21-24] and [25], geophysical method such as the electrical resistivity can be practically adopted to determine the internal distribution of materials within a slope, identifying sliding surface geometry, water effect on slope, landslide material physical properties and mass movement. Furthermore, electrical resistivity data was able to show a two layer system in which the low resistivity landslide mass cross-cuts the resistivity layering in the higher resistivity sediments [26]. However, the standard performance of individual geophysical method always depends on fundamental physical limitation (e.g. penetration, resolution, and signal to-noise ratio) [21] and [27]. Moreover, geophysical methods are unable to stand alone in order to provide solutions to any particular problems [28] and [29]. Hence, strong verification from direct test (field test, experimental test, etc.) was important to support the electrical resistivity anomaly interpretation. A number of researchers have shown that the integration of geophysical survey and geotechnical data can provide a meaningful data and interpretation for subsurface profile characterization [30-32] and [20].

Hence, this study performed a forensic assessment on near surface landslide using electrical resistivity imaging (ERI) at Kenyir Lake area in Terengganu, Malaysia. Finally, this study aims to contribute those related parties regarding the good prospect of ERI as an alternative tool in forensic landslide investigation.

2. Methodology

This study involves three phases via desk study, field measurement and data processing. Desk study begins with gathering of previous information regarding study area thru existing report, maps, etc. due to obtained early information such as sites geology, topography, etc. in global and localize scale as presented in subsection 2.1. Then, field measurement was performed using electrical resistivity imaging (ERI) and finally raw data from field measurement was analyzed and processed using RES2DINV software as explained in subsection 2.2.

2.1. Study area and geologic setting

This study was located at north eastside of Peninsular Malaysia consist of an artificial lake (largest man-made lake in South East Asia) in the state of Terengganu created in 1985. Generally, the site study has mix topography of undulating hilly terrain which surrounds the existing reservoir. The localize site study was performed at Kenyir Lake, Terengganu specifically at Pengkalan Gawi as shown in Figure 1.

The general geology of Malaysia has been well documented by Minerals and Geoscience Department Malaysia (1985). Geological map in Figure 2 shows distribution the bedrock in this studied area which specifically located at Pengkalan Gawi, Kenyir Lake. According to Figure 1, Pengkalan Gawi, Kenyir Lake is situated at intrusive rock formation which is granitic rock consist of fault zone. In addition, Figure 3 shows positive lineament of satellite image as evidence that Pengkalan Gawi, Kenyir Lake was located in a fault zone. This fault may possibly presents and influencing the investigated area, thus provide a groundwater regime in the rock formation. Site observation indicated the granitic outcrop and boulder. Based on boreholes results, it was found that this area has been a mixture of sandy silt, silty sand, clayey silt and gravelly sand. Borehole records (BH 1 and BH 2) also revealed that this area was formed by granitic bedrock.

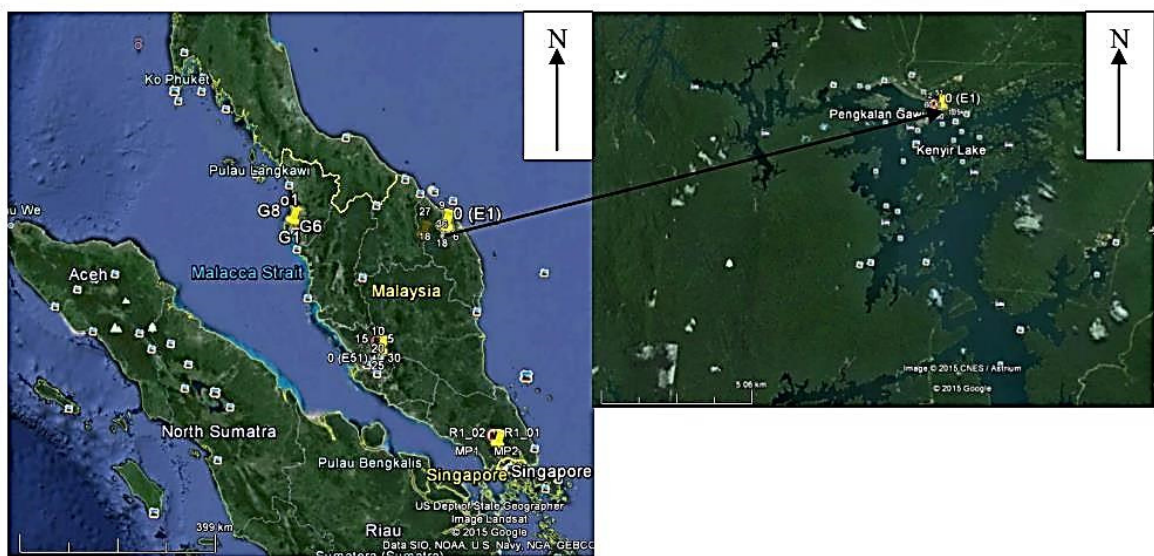


Fig. 1. Study area.

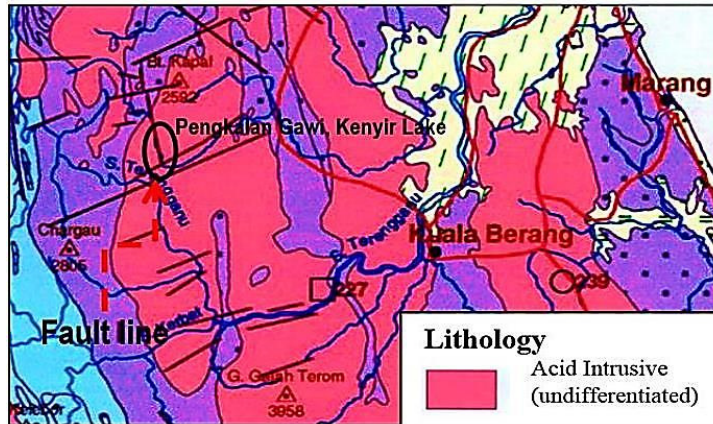


Fig 2. Geology of the study area [33].

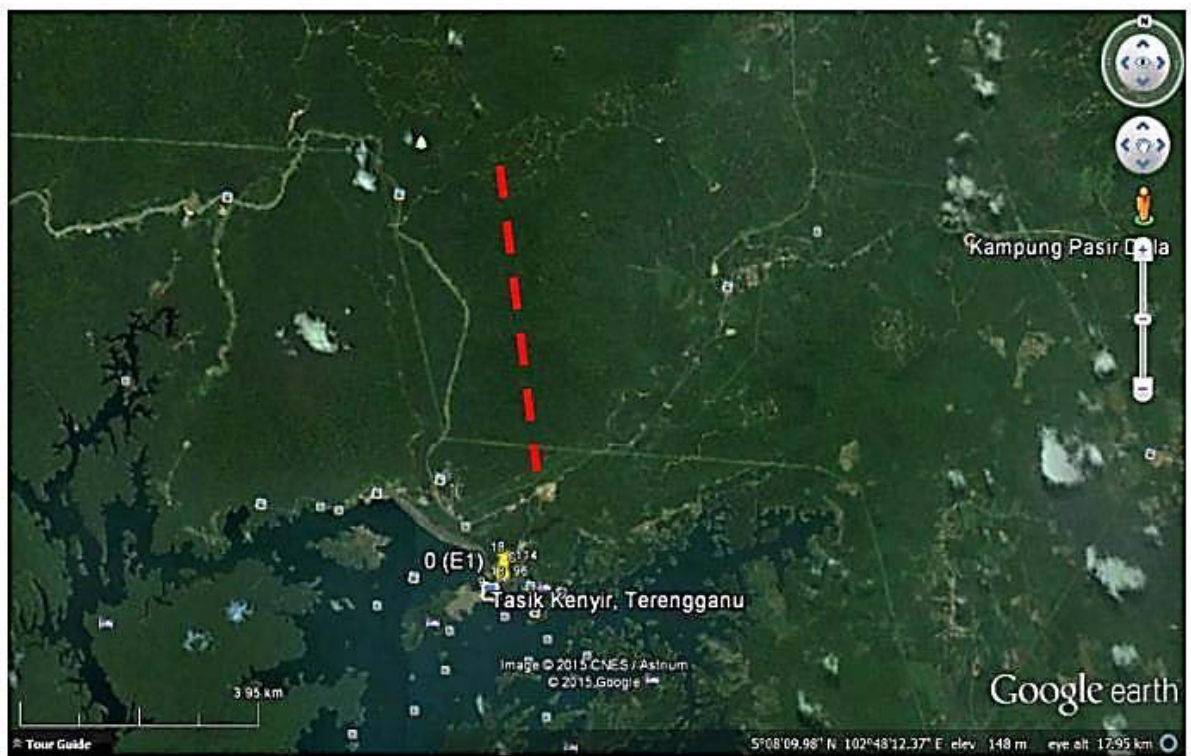


Fig. 3. Positive lineament from satellite image as an evidence that Pengkalan Gawi, Kenyir Lake located in a fault zone.

2.2. Equipment

The electrical resistivity equipment consists of three main components; viz. source, inducer and record. The electrical resistivity source was generated using a 12 volt of DC battery. A 53 steel electrode was used as a current inducer medium while ABEM Terrameter LS was used to record the apparent resistivity value. The raw data measured on site was analyzed and interpreted by RES2DINV software.

2.3. Data acquisition and processing

Electrical resistivity imaging (ERI) was performed using ABEM Terrameter LS equipment set. Two (2) spread lines of electrical resistivity survey were performed across the problematic study area as shown in Figure 4. Testing configuration was based on Schlumberger array using three resistivity land cables, fifty one (51) numbers of electrode and fifty three (53) numbers of jumper cable. Equal electrode spacing of 3.0 m was used for all 51 electrodes producing total electrical resistivity survey length of 180 m. Field arrangement of the electrical resistivity imaging was given in Figure 5. Schlumberger array was used during the data acquisition since it able to provide dense near-surface cover of resistivity data. As reported by [34], the array provides a good vertical resolution and can give a clear image of groundwater and sand-clay boundaries as horizontal structures. Furthermore, the array able to provide greater depth of subsurface profiles within limited spaced area during the resistivity data acquisition. Raw data obtained from data acquisition were firstly being processed using commercialize RES2DINV software of [35] to provide an inverse model that approximates the actual subsurface structure. The inversion algorithm of RES2DINV was used to process the data, as proposed by [36] in order to obtain the 2-D resistivity section. The inversion routine used by the program RES2DINV was based on the robust constrained method due to the target interest (subsurface deformation) and site condition.

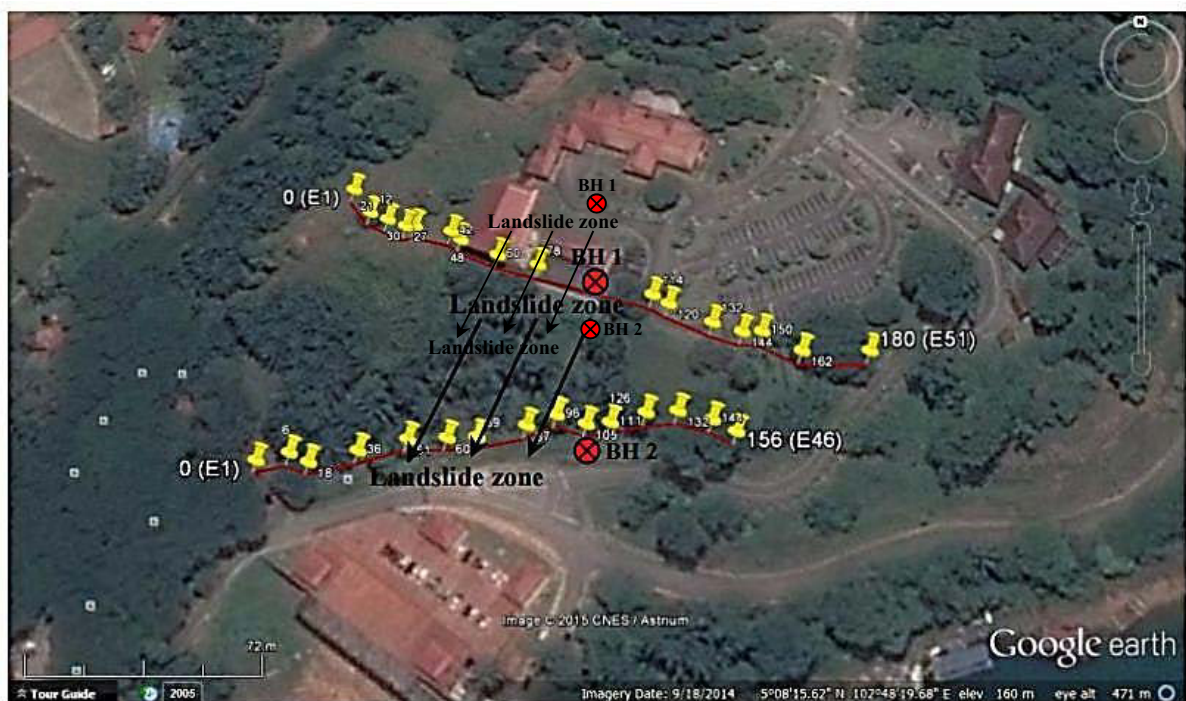


Fig. 4. Location of the entire electrical resistivity lines (spread lines) performed at Pengkalan Gawi Tasik Kenyir, Terengganu.

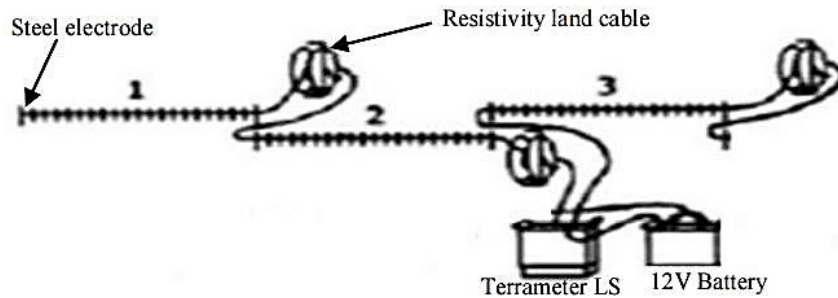


Fig. 5. Field arrangement of electrical resistivity imaging (ERI) based on three cables configuration.

3. Results and discussions

Two (2) profiles of two-dimensional (2D) electrical resistivity tomography (ERT) were obtained from the field surveys at the selected area in Kenyir Lake Terengganu, Malaysia. Subsurface profile mapping generated by surface mapping of electrical resistivity method was produced thru ERT as given in Figure 6 and 7 respectively. The ERT result and interpretation spread lines 1 and 2 was verified thru the existing boreholes (BH 1 and BH 2) located along of each spread lines as shown in Figure 6 and 7 respectively. Generally, both ERT at Figure 6 and 7 composed of materials from completely weathered to highly weathered zone (1 – 150 ohm.m), highly weathered to moderately weathered (150 – 300 ohm.m), moderately weathered to hard material (300 – 2400 ohm.m) and fresh, hard and dry material (2400 ohm.m & over). Electrical resistivity value (ERV) was determined by measuring the potential difference at points on the ground surface which caused the propagation of direct current through the subsurface [37]. Electrical resistivity value can be influenced by several factors such as the concentration and type of ions in pore fluid and grain matrix of geomaterials via the process of electrolysis where the current was carried by ions at a comparatively slow rate [38]. According to [12], a soil's electrical resistivity value generally varies inversely proportional to the water content and dissolved ion concentration as clayey soil exhibit high dissolved ion concentration, wet clayey soils have lowest resistivity of all soil materials while coarse, dry sand and gravel deposits and massive bedded and hard bedrocks have the highest ERV. As reported by [39], a decrease of ERV was results from an increase of metal ions or inorganic elements in geomaterials. As reported by [40-42], [5] and [43], soil resistivity value can be varied due to the variation of basic geotechnical properties such as moisture content, densities, void ratio, porosity and grain size fraction. Furthermore, condition such as porosity, degree of saturation, salt concentration in pore fluid, grain size, size gradation, temperature and activity may influence to the electrical resistivity value variations [44].

The resistivity image (ERT) for spread line 1 was able to obtain the maximum depth of penetration with up to 20 m. Figure 6 shows the vast range of resistivity value within for spread line 1 shows that highly heterogenous material. At the center of resistivity line, blue color of ERV (< 150 ohm.m) has been classify as completely weathered to highly weathered zone. This zone was possibly composed of soil with water and weak cohesive soil and highly fractured rock. According to BH 1, soil profile consists of sandy SILT to clayey SILT which represented by ERV of 150 ohm.m and below subjected to moisture and grain size variations. According to [45], ERV of clayey and silty soils was varies from 1 – 150 ohm.m. Moreover, [14] was reported that the ERV of clay and silt material can be varied from 1 – 500 ohm.m subjected to moisture and grain size variations. Both sides of the ERT (Figure 6) consists of moderately weathered to hard material (300 – 2400 ohm.m) which possibly derived from moderately fractured to hard/dry material with dry soil filled cracks; sand and gravel with layers of silt & weathered rock [45]. The resistivity value larger than 2400 ohm.m was classified as fresh, hard and dry material which possibly composed from massive bedded and hard bedrock; coarse dry and gravel deposits [45]. According to BH 1, inconsistent layer of soil consistency was varied from medium-stiff-medium-soft (SPT (N) = 6 – 9 – 8 – 4). Furthermore, shallow rock head was detected at depth of 7.5 m with its poor-fair-good description of rock quality designation (RQD = 40% – 60%– 80%). Hence, the results obtained from BH 1 shows that the subsurface profile consist of heterogeneous profile thus verified the ERT result and interpretation for spread line 1. According to BH 1, groundwater table was detected at 6.3 m which also indicates that the ground can possibly instable.

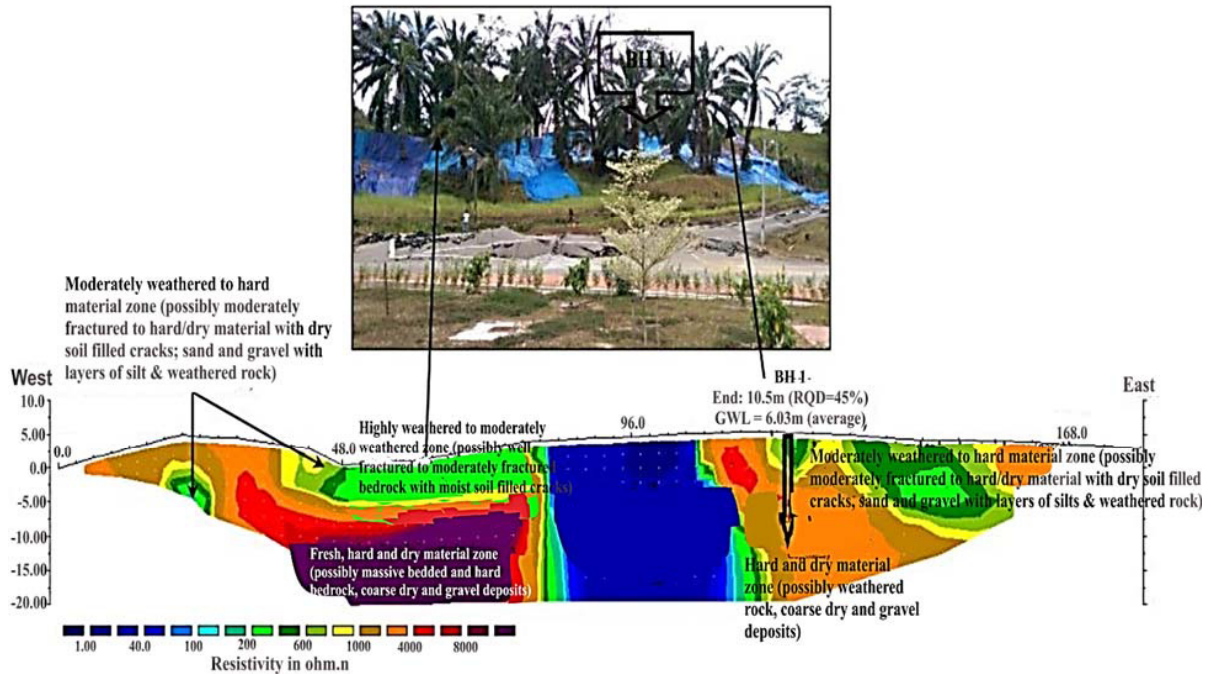


Fig. 6. Electrical resistivity tomography (ERT) for spread line 1 generated at top of the slope (West-East direction).

The resistivity image (ERT) for spread line 2 was able to obtain the maximum depth of penetration with up to 20 m. Figure 7 shows the vast range of resistivity value within for spread line 2 shows that highly heterogeneous material. At the center of resistivity line, blue color of ERV (< 150 ohm.m) has been classified as completely weathered to highly weathered zone. This zone was possibly composed of soil with water and weak cohesive soil and highly fractured rock. According to BH 2, soil profile consist of sandy SILT and silty SAND which represented by ERV of 150 ohm.m and below subjected to moisture and grain size variations. According to [45], ERV of silty and sandy soils was varies from 3 – 150 ohm.m. Moreover, [14] was reported that the ERV of clay and silt material can be varied from 1 – 500 ohm.m subjected to moisture and grain size variations. Both sides of the ERT (Figure 7) consists of highly weathered to moderately weathered zone (150 – 300 ohm.m) which possibly consists of well fractured to moderately fractured bedrock with moist soil filled cracks [45]. The resistivity value larger than 2400 ohm.m has been classified as fresh, hard and dry material which possibly composed of massive bedded and hard bedrock; coarse dry and gravel deposits [45]. According to BH 2, inconsistent layer of soil consistency was varied from medium-stiff-very stiff (SPT (N) = 9 – 12 – 14 – 12 – 15 – 14 – 8 – 11 – 10 – 13 – 15 – 12 – 18). Furthermore as referred to BH 1-2, it was found that the subsurface profile consist of deep rock head (21.1 m) with fair rock quality designation (RQD = 65%). Hence, the results obtained from BH 2 shows that the subsurface profile consist of heterogeneous profile thus verified the ERT result and interpretation for spread line 2. According to BH 2, groundwater table was detected at 5.03 m which also indicates that the ground can possibly instable.

Generally, the entire ERT (Figure 8) has shown that the subsurface profile has been dominated by weak materials at the center of each profile continuously. Historically, this area presents geological structure with particular reference to fault line (Figure 3) which consider weak due to its heterogeneous geomaterials. Hence, landslides phenomenon in this area was possibly triggered by heavy precipitation due to rain water that flow and seep thru the geological structure with particular reference to fault zone. This landslide tragedy was occurred during the raining season (December 2015) thus influencing the activation of weakness zone (fault zone) due to excessive pore water pressure. This judgment was made due to the verification thru established geological map [33] which indicates the existing of fault line symbol as shown in Figure 2. Commonly, low electrical resistivity value (ERV) will indicate the existing of the weak zone, which

may contain high water content or highly conductive materials. As a result, it is possible to think that weak zone of subsurface geomaterials in natural slope is likely to show a low resistivity value due to the high conductive zone which commonly contained water [46]. Based on Figure 8, deformation zone geometry due to the water and fault line influences was able to be approximated by 36 m (width) and 40 m and over (depth). According to [26], reduction of ERV may related to increased water content that would lower the ERV of sheared materials, development of shear zones that lower the ERV for the sliding materials and alteration through weathering may reduce the ERV in the sliding zone. This study has demonstrated that the ERT (2D) result from Figure 8 was able to contribute to the estimation of destructive zone (landslides due to the fault line) in contrast to the boreholes (1D) method. As reported by [47], geophysical surveys supplemented shallow boreholes to extend the subsurface data to greater depths. It was highly recommended that the resistivity survey need to be performed earlier than the borehole drilling exploration due to decide the most suitable point location of boreholes.

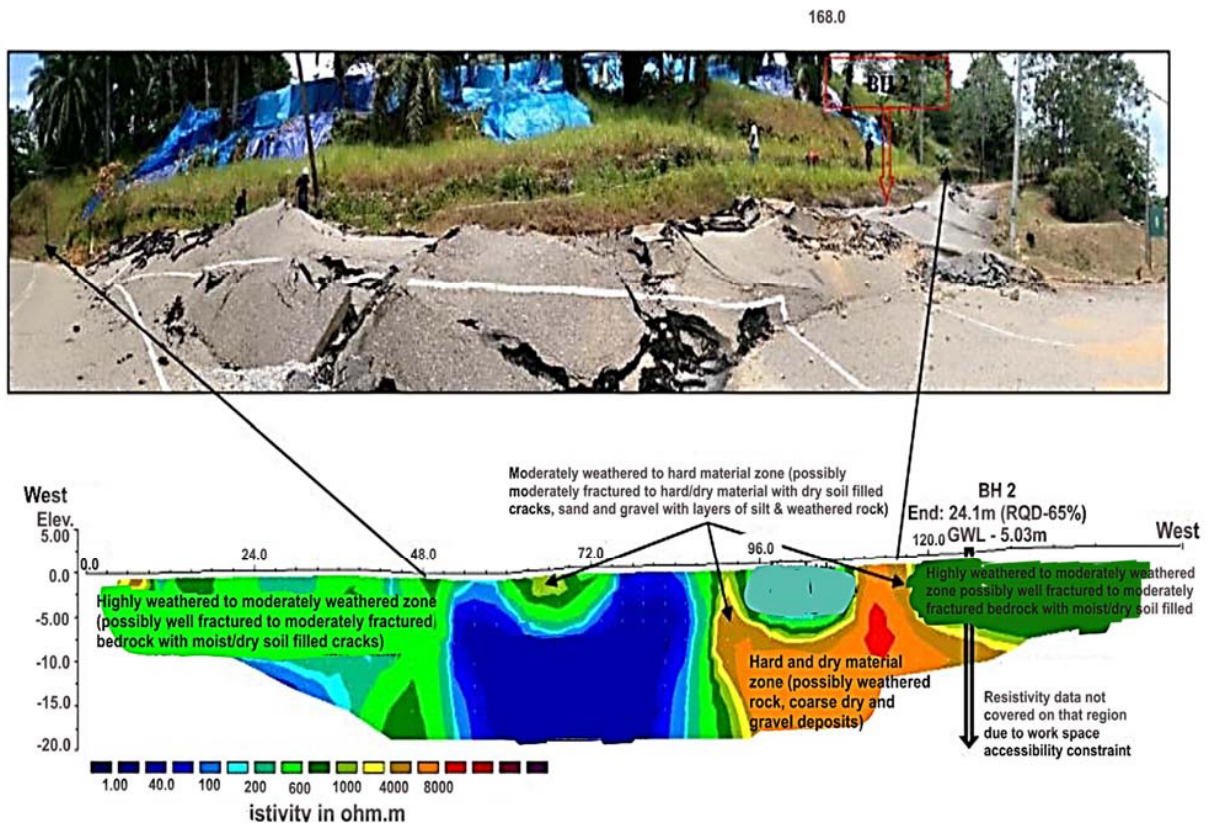


Fig. 7: Electrical resistivity tomography (ERT) for spread line 2 generated at toe of the slope (West-East direction)

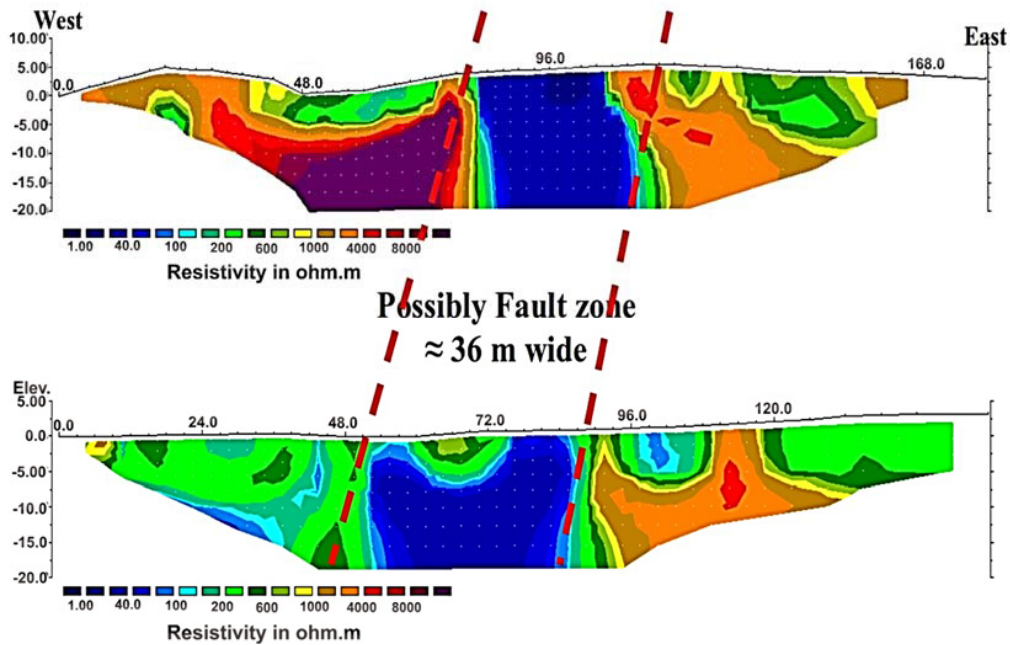


Fig. 8: Arrangement of all resistivity results based on site position (Top and bottom of the landslide).

4. Conclusions

The problematic subsurface profile in landslides was successfully being investigated using electrical resistivity tomography (ERT). The geometry and electrical resistivity distribution of localize landslides at Kenyir Lake area, Terengganu, Malaysia has determined by analyzing electrical resistivity data obtained and the result has generally shown a very good agreement with drilling data. This finding has proved that this method is able to predict the landslides features in order to assist the conventional borehole data. ERT was successfully mapped the subsurface profile which able to extend the surface information mapped by geodynamic mapping and other physical mapping. The mechanics and physical characteristics of the landslide can be easily recognized. The determination of shape and depth of the subsurface landslide which caused ground damage are easier and cheaper than with conventional borehole method. The information from the electrical resistivity results was useful for rehabilitation and mitigation purposes. This geophysical method is suitable for our sustainable ground investigation since it can reduce time, money and compliment others conventional method especially by its 2D surface technique of investigation. The application of electrical resistivity tomography in conjunction with geological and borehole information was effectively being applied for forensic assessment with particular reference of near surface landslides.

Acknowledgements

Thank are due to all research members for their tremendous work and cooperation. Many thanks go to Universiti Tun Hussein Onn Malaysia for the sponsor and financial support (IGSP from Vot U258) throughout this research activity.

References

- [1] H.G Poulos, A Framework for Forensic Foundation Engineering, in: Proc. International Conference on Forensic Engineering: From Failure to Understanding, London, 2008, pp. 247.
- [2] I. Anastasopoulos, Building damage during nearby construction: Forensic analysis, Engineering Failure Analysis. 34 (2013) 252–267.

- [3] G. Russo, V. Abagnara, H. Poulos, J. Small, Re-assessment of foundation settlements for the Burj Khalifa, Dubai *Acta Geotechnica*. 8 (2013) 3–15.
- [4] L. Pando, J. Pulgar, M. Gutiérrez-Claverol, A case of man-induced ground subsidence and building settlement related to karstified gypsum (Oviedo, NW Spain), *Environmental Earth Sciences*. 68 (2012) 507–519.
- [5] M.H.Z. Abidin, F. Ahmad, D.C. Wijeyesekera, R. Saad, M.F.T. Baharuddin Soil Resistivity Measurements to Predict Moisture Content and Density in Loose and Dense Soil, *Applied Mechanics and Materials*. 353–356 (2013) 911–917.
- [6] A. Godio, C. Strobbia, G. De Bacco, Geophysical Characterisation of a Rockslide in an Alpine Region, *Engineering Geology*. 83 (2006) 273–286.
- [7] H. J. Mauritsch, W. Seiberl, R. Arndt, A. Römer, K. Schneiderbauer, G.P. Sendlhofer, Geophysical Investigations of Large Landslides in the Carnic Region of Southern Austria, *Engineering Geology*. 56 (2000) 373–388.
- [8] R. Frigaszy, J. Santamarina, A. Amekudzi, D. Assimaki, R. Bachus, S. Burns, M. Cha, G. Cho, D. Cortes, S. Dai, D. Espinoza, L. Garrow, H. Huang, J. Jang, J. Jung, S. Kim, K. Kurtis, C. Lee, C. Pasten, H. Phadnis, G. Rix, H. Shin, M. Torres, C. Tsouris Sustainable development and energy geotechnology — Potential roles for geotechnical engineering, *KSCE Journal of Civil Engineering*. 15 (2011) 611–621.
- [9] C.R.I. Clayton, M.C. Matthews, N.E. Simons, Site Investigation, Blackwell Science Ltd, UK, 1995.
- [10] Z.A.M. Hazreek, S. Rosli, D.C. Chitral, A. Fauziah, A.T.S. Azhar, M. Aziman, B. Ismail, Soil Identification using Field Electrical Resistivity Method, *Journal of Physics: Conference Series*. 622 (2015) 1–7.
- [11] R. Khatri, V.K. Shrivastava, R. Chandak, Correlation between vertical electric sounding and conventional methods of geotechnical site investigation, *Int. Journal of Advanced Engineering Sciences and Technologies*. 4 (2011) 042–053.
- [12] C. Liu, J.B. Evett, *Soils and Foundation*, Pearson International, New Jersey, 2008.
- [13] P. Cosenza, E. Marmet, F. Rejiba, Y. Jun Cui, A. Tabbagh, Y. Charlery, Correlations between geotechnical and electrical data: A case study at Garchy in France, *Journal of Applied Geophysics*. 60 (2006) 165–178.
- [14] T. S. Lee: *Slope Stability and Stabilization Methods*, John Wiley & Sons, Inc. New York, 2002.
- [15] M.H. Loke, J.E. Chambers, D.F. Rucker, O. Kuras, P.B. Wilkinson, Recent developments in the direct-current geoelectrical imaging method, *Journal of Applied Geophysics*. 95 (2013) 135–156.
- [16] G. Grandjean, J.C. Gourry, O. Sanchez, A. Bitri, S Garambois, Structural study of the Ballandaz landslide (French Alps) using geophysical imagery, *Journal of Applied Geophysics*. 75 (2011) 531–542.
- [17] M.I. Kim, J.S. Kim, N.W. Kim, G.C Jeong, Surface geophysical investigations of landslide at the Wiri area in southeastern Korea, *Environmental Earth Sciences*. 63 (2011) 999–1009.
- [18] S. Friedel, A. Thielen, S.M. Springman, Investigation of a slope endangered by rainfall-induced landslides using 3D resistivity tomography and geotechnical testing, *Journal of Applied Geophysics*. 60 (2006) 100–114.
- [19] A. Godio, G. Bottino, Electrical and electromagnetic investigation for landslide characterisation. *Physics and Chemistry of the Earth, Part C: Solar, Terrestrial and amp, Planetary Science*. 26 (2001) 705–710.
- [20] R. Hack, *Geophysics for Slope Stability*, *Surveys in Geophysics*. 21 (2000) 423–448.
- [21] H.J. Mauritsch, W. Seiberl, R. Arndt, A. Römer, K. Schneiderbauer, G.P. Sendlhofer, Geophysical investigations of large landslides in the Carnic Region of southern Austria, *Engineering Geology*. 56 (2000) 373–388.
- [22] A. Perrone, V. Lapenna, S. Piscitelli, Electrical resistivity tomography technique for landslide investigation: A review, *Earth-Science Reviews*. 135 (2014) 65–82.
- [23] G. Göktürkler, C. Balkaya, Z. Erhan, Geophysical investigation of a landslide: The Altindag landslide site, Izmir (western Turkey), *Journal of Applied Geophysics*. 65 (2008) 84–96.
- [24] D.M. McCann, A. Forster, Reconnaissance geophysical methods in landslide investigations, *Engineering Geology*. 29 (1990) 59–78.
- [25] V.A. Bogoslovsky, A.A Ogilvy, Geophysical methods for the investigation of landslides. *International Journal of Rock Mechanics and Mining Sciences & amp, Geomechanics Abstracts*. 15 (1978) 562–571.
- [26] D.F. Palmer, S.L. Weisgarber, Geophysical survey of the Stump Basin Landslide, Ohio, *Bulletin Association of Engineering Geologist*. 3 (1988) 363–370.
- [27] D.M. McCann, A. Forster, Reconnaissance geophysical methods in landslide investigations, *Engineering Geology*. 29 (1990) 59–78.
- [28] S.G.C. Fraiha, J.B.C. Silva, Factor analysis of ambiguity in geophysics, *Geophysics*. 59 (1994) 1083–1091.
- [29] R.C. Benson, L. Yuhr, R.D. Kaufmann, Some Considerations for Selection and Successful Application of Surface Geophysical Methods, in: *Proc. The 3rd Int. Conf. on Applied Geophysics*, Orlando, Florida, 2003.
- [30] H. Almalki, A.K. El-Werr, K. Abdel-Rahman, Estimation of near-surface geotechnical parameters using seismic measurements at the proposed KACST expansion site, Riyadh, KSA, *Arabian Journal of Geosciences*. 4 (2011) 1131–1150.
- [31] K. Sudha, M. Israil, S. Mittal, J. Rai, Soil characterization using electrical resistivity tomography and geotechnical investigations, *Journal of Applied Geophysics*. 67 (2009) 74–79.
- [32] S. Oh, C.G. Sun, Combined analysis of electrical resistivity and geotechnical SPT blow counts for the safety assessment of fill dam, *Environmental Geology*. 54 (2008) 31–42.
- [33] Minerals and Geoscience Department Malaysia, *Geological Map of Peninsular Malaysia*, 8th Ed. Ministry of Natural Resources and Environment, 1985.
- [34] U. Hamzah, R. Yaacup, A.R. Samsudin, M.S Ayub, Electrical imaging of the Groundwater Aquifer at Banting, Selangor, Malaysia, *Environmental Geology*. 49 (2006) 1156–1162.
- [35] M.H. Loke, I. Acworth, T. Dahlin, A comparison of smooth and blocky inversion methods 2-D electrical imaging surveys, *Exploration Geophysics*. 34 (2003) 182–187.

- [36] M.H. Loke, R.D. Barker, Rapid least squares inversion of apparent resistivity pseudosection using a quasi-Newton method, *Geophysical Prospecting*. 44 (1996) 131–152.
- [37] H.R. Burger, A.F. Sheehan, C.H. Jones, *Introduction to Applied Geophysics*, W.W. Norton & Company, New York, 2006.
- [38] D.H. Griffiths, R.F. King, *Applied Geophysics for Geologist and Engineers The Element of Geophysical Prospecting*, Pergamon Press, Oxford, 1981.
- [39] Y. Jung, Y. Lee and H. Ha, Application of electrical resistivity imaging techniques to civil and environmental problems, *Use of Geophysical Methods in Construction*, 2000.
- [40] M.H.Z. Abidin, R. Saad, F. Ahmad, D.C. Wijeyesekera and M.F.T. Baharuddin, Correlation analysis between field electrical resistivity value (ERV) and basic geotechnical properties (BGP), *Soil Mechanics and Foundation Engineering*. 51 (2014) 117–125.
- [41] M.H.Z. Abidin, F. Ahmad, D.C. Wijeyesekera and R. Saad, The influence of basic physical properties of soil on its electrical resistivity value under loose and dense condition, *Journal of Physics: Conference Series*. (2014) 1–13.
- [42] M.H.Z. Abidin, F. Ahmad, D.C. Wijeyesekera and R. Saad, Small soil embankment electrical resistivity value on its array, moisture content and density influences. *International Journal of Geology*. 8 (2014) 9–18.
- [43] M.H.Z. Abidin, D.C. Wijeyesekera, R. Saad and F. Ahmad, The influence of soil moisture content and grain size characteristics on its field electrical resistivity, *Electronic Journal of Geotechnical Engineering*. 18/D (2013) 699–705.
- [44] V.A. Rinaldi, G. Cuestas, Ohmic Conductivity of a Compacted Silty Clay, *Journal of Geotechnical and Geoenvironmental Engineering*. 128 (2002) 824–835.
- [45] D.F. McCarthy, *Essentials of Soil Mechanics and Foundations Basic Geotechnics*, Pearson International Edition, New Jersey, 2007.
- [46] M.H.Z. Abidin, R. Saad, F. Ahmad, D.C. Wijeyesekera, M.F.T. Baharuddin, Integral analysis of geoelectrical (resistivity) and geotechnical (SPT) data in slope stability assessment, *Academic Journal of Science*. (2012) 305–316.
- [47] D. Cummings, B.R. Clark, Use of seismic refraction and electrical resistivity surveys in landslides investigations, *Bulletin Association of Engineering Geologists*. 4 (1988) 459–464.